

I. SUMMARY OF RESEARCH

Before 1966, the problems of fuel sloshing and its suppression during thrusting or for large axial acceleration conditions (high Bond numbers) were well understood, but corresponding knowledge of their behavior during periods of low accelerations (low Bond numbers) was rather meagre and specialized. Consequently, the chief objectives of our research were to study lateral sloshing of liquids in axisymmetric tanks under *low-gravity* conditions and to derive equivalent mechanical models of the sloshing for use in stability and control analyses. We studied only liquids and tank materials that have a "zero-degree contact angle," for which the liquid free surface is highly curved in a low-gravity environment, because it is this condition which is apparently encountered in space vehicle applications.

Although the chief objectives of this study concerned low-gravity behavior, a study of flexible baffles for slosh suppression in high Bond number conditions constituted a small effort at the start of the research program. The results of this study are now additionally significant due to the suggestion by NASA that such baffles may be employed in the Space Shuttle Vehicle.

Experimental data during the low-gravity sloshing phase of the program were obtained by *simulating* a low-gravity environment. A preliminary study of possible simulation techniques indicated that we could obtain reliable data on slosh natural frequency, slosh forces, and slosh damping by using *small models* to achieve low values of the Bond number for various tank shapes. We subsequently refined this technique to where it is now a precise and sensitive research tool. The data obtained by this method are generally limited to Bond numbers greater than about 10, which still covers the range of interest for large vehicles in coasting orbits. To obtain data for smaller Bond numbers and thus to approach more closely zero-gravity, we also conducted a series of exploratory tests using a *magnetic-colloid liquid* and a solenoidal magnet field such that the effective gravity acting on the liquid could be varied at will. Even though it was not possible to completely optimize our experimental method during the contract period, we obtained reliable data for effective gravities as small as 1 percent of standard gravity and Bond numbers as small as unity. We believe that with further refinement the magnetic liquid method could be made to yield reliable data at effective gravity levels of an order of magnitude smaller than we achieved in these preliminary tests.

The analytical work conducted for this contract dealt with the characteristics of inviscid fuel sloshing in axisymmetric tanks for arbitrary values of the Bond number, and we derived the first known equivalent mechanical model of fuel sloshing in low-gravity environments during the research. The culmination of the analytical efforts was a generalized computer program that predicts the natural frequencies and mode shapes for fuel sloshing in an arbitrary axisymmetric container.

The results of our program are detailed in ten technical reports and six published papers, which are discussed in the following section.

II. DOCUMENTATION

A. Technical Reports

Details of all aspects of the work performed on Contract NAS 8-20290 are given in the ten technical reports listed below. For convenience to the reader, the abstract of each report is given also.

1. Technical Report No. 1, "A Comparison of Flexible and Rigid Ring Baffles for Slosh Suppression," by Luis R. Garza, August 17, 1966.

A test program to determine the effectiveness of flexible ring baffles as liquid slosh suppressors was conducted. A comparison of flexible and rigid ring baffles is presented in terms of liquid damping, first mode sloshing resonant frequency, and maximum baffle depth for no rotational slosh.

2. Technical Report No. 2, "Experimental and Theoretical Studies of Liquid Sloshing at Simulated Low Gravities," by Franklin T. Dodge and Luis R. Garza, October 20, 1966.

An analysis is given for liquid sloshing in a rigid cylindrical tank under conditions of moderately low gravitational acceleration; the theory is valid for Bond numbers that are larger than 10. The results are put in the form of an equivalent mechanical model. It is found that both the fundamental sloshing mass and the natural frequency, for a liquid having a zero-degree contact angle, are smaller than for the usual high-g sloshing.

A series of experiments was conducted to determine the sloshing force and the natural frequency for Bond numbers between 10 and 200. The test results are compared to the theoretical predictions of the mechanical model, and good correlation between theory and experiment is shown.

3. Technical Report No. 3, "A Discussion of Laboratory Methods of Simulating Low-Gravity Fluid Mechanics," by Franklin T. Dodge, February 1967.

Methods of simulating the behavior of liquids in a low-gravity environment by experiments in Earth based laboratories are discussed, with an attempt made to point out the advantages and limitations of each. Two promising methods are indicated: small models, and magnetic liquids. It is concluded that these methods should be developed further, not only to complement orbital experiments but also to give preliminary data at low cost.

4. Technical Report No. 4, "Low Gravity Liquid Sloshing in an Arbitrary Axisymmetric Tank Performing Translational Oscillations," by Wen-Hwa Chu, March 20, 1967.

The title problem is solved by using characteristic functions. The force and moment due to lateral translation of a rigid axisymmetric tank are obtained. However, no numerical example is given because of the considerable programming effort required.

5. Technical Report No. 5, "Simulated Low-Gravity Sloshing in Cylindrical Tanks Including Effects of Damping and Small Liquid Depth," by Franklin T. Dodge and Luis R. Garza, December 29, 1967.

Liquid sloshing in cylindrical tanks is studied under conditions of simulated low gravities. The effects of finite liquid depths and the determination of the smooth wall damping are emphasized. The experimental and theoretical results show that the fluid dynamics are affected by small h/d ratios in much the same way as for normal, large Bond number sloshing. Measurements of the slosh damping indicate that the damping increases as the Bond number decreases, and two correlation equations for the damping factor are proposed. An equivalent mechanical model developed

previously is extended to include h/d variations and linear viscous damping. Comparisons of the force response predicted by the model to that measured in the tests verify the model to a high degree of confidence.

6. Technical Report No. 6, "Simulated Low-Gravity Sloshing in Spherical Tanks and Cylindrical Tanks with Inverted Ellipsoidal Bottoms," by Franklin T. Dodge and Luis R. Garza, February 1968 (includes errata sheet for Tech. Rept. No. 5).

Liquid sloshing in cylindrical tanks having inverted ellipsoidal bottoms and in spherical tanks is studied experimentally under conditions of simulated low gravities. The effects of variable liquid depth and the determination of smooth wall damping are emphasized. Results from cylindrical tanks are qualitatively similar to results obtained previously with cylindrical tanks having flat bottoms; significant differences from previous results for natural frequency and slosh damping are apparent, however, for small liquid depths. Correlation equations for the damping coefficient as a function of h/d , N_{GA} , and N_{BO} are presented. Results from spherical tanks show that the variation in free-surface curvature with liquid depth has a strong effect on the natural frequency; in fact, increased curvature in spherical tanks as compared to cylindrical tanks causes the natural frequency to decrease as N_{BO} decreases, which is just the opposite of the variation obtained with cylindrical tanks. The damping in spherical tanks is shown to be a minimum when the tank is half-full; when $h_{av}/d = 0.50$ (half-full), γ_s is about 50% less than γ_s when $h_{av}/d = 0.25$, and about 10 to 20% less than when $h_{av}/d = 0.75$.

7. Technical Report No. 7, "Slosh Force, Natural Frequency, and Damping of Low-Gravity Sloshing in Oblate Ellipsoidal Tanks," by Franklin T. Dodge and Luis R. Garza, February 1969.

Liquid sloshing in oblate ellipsoidal tanks is studied experimentally under conditions of simulated low gravities. The results demonstrate that the variation of free-surface curvature with liquid depth has a strong influence on natural frequency; for tanks over one-half full, the frequency decreases markedly as the Bond number is decreased. Moreover, the force response characteristics show that the mass of liquid participating in the sloshing is, in every case, less than the corresponding sloshing mass for a flat free surface. Calculations of the slosh damping show it to be a function of the liquid level, the Bond number, and the Galileo number.

8. Technical Report No. 8, "Low-Gravity Fuel Sloshing in an Arbitrary Axisymmetric Rigid Tank," by Wen-Hwa Chu, April 1969.

Solutions to free and forced oscillations have been found in terms of an auxiliary set of eigenfunctions. The slosh force and moment for an arbitrary axisymmetric rigid tank at arbitrary Bond number have been derived for both pitching and translation and expressed in terms of characteristics of an equivalent spring-mass system. Numerical examples have been constructed which compare favorably with available theories and experiments.

9. Technical Report No. 9, "Magnetic Fluid Simulation of Liquid Sloshing in Low Gravity," by Franklin T. Dodge and Luis R. Garza, August 1970.

An exploratory series of tests of simulated low-gravity liquid sloshing using a magnetic-colloid liquid in conjunction with a solenoidal magnetic field is described herein. A description of the experimental apparatus and test procedure is also presented.

The magnetic body-force exerted on the liquid was varied by changing the magnetic field strength in order to obtain effective gravities as small as 0.01 g. The measured slosh natural frequencies for both cylindrical and spherical tanks in these low-gravity conditions agreed very well with theoretical predictions. Slosh damping, however, was significantly larger than expected because of the increase in viscosity of magnetic liquids due to magnetic field effects.

A magnetic-fluid analysis of sloshing is presented, and indicates that some deviation from true low-gravity behavior might occur whenever the Bond number is smaller than one. The discrepancy is caused by a magnetic interaction at the free surface that induces a jump in liquid pressure similar to that induced by surface tension.

10. Technical Report No. 10, "A Computer Program for Fuel Sloshing in an Axisymmetric Tank," by W. H. Chu, R. Gonzales, A. F. Muller, and D. R. Saathoff, August 1970.

This report describes the use of the computer program developed to implement the analyses presented in Technical Report No. 8.

B. Published Papers and Notes

Five published technical papers and notes present the main results of the research program through Technical Report No. 8. A further paper is being prepared to present the results given in Technical Report No. 9.

Titles of the published material are listed below, and a reprint of each publication is given in the Appendix.

1. Garza, Luis R., and Dodge, Franklin T., "A Comparison of Flexible and Rigid Ring Baffles for Slosh Suppression," *AIAA Journal of Spacecraft and Rockets*, 4, No. 6, June 1967, pp 805-806.
2. Dodge, F. T., and Garza, L. R., "Experimental and Theoretical Studies of Liquid Sloshing at Simulated Low Gravity," *Transactions ASME, Journal of Applied Mechanics*, 34, No. 3, Sept. 1967, pp 555-561.
3. Dodge, Franklin T., and Garza, L. R., "Simulated Low-Gravity Sloshing in Cylindrical Tanks Including Effects of Damping and Small Liquid Depth," **Proceedings of the 1968 Heat Transfer and Fluid Mechanics Institute**, Ashley F. Emery and Creighton A. Depew, Editors, Stanford University Press, 1968, pp 67-79.
4. Dodge, Franklin T., and Garza, Luis R., "Simulated Low-Gravity Sloshing in Spherical, Ellipsoidal, and Cylindrical Tanks," *AIAA Journal of Spacecraft and Rockets*, 7, No. 2, February 1970, pp 204-206.
5. Chu, Wen-Hwa, "A Theory for Low-Gravity Fuel Sloshing in an Arbitrary Axisymmetric Rigid Tank," ASME Paper No. 70-APM-EEE. To appear in *Transactions ASME, Journal of Applied Mechanics*.
6. Dodge, Franklin T., and Garza, Luis R., "Magnetic Fluid Simulation of Sloshing in Low Gravity," paper in preparation.

APPENDIX

Reprints of Papers and Notes Issued Under Contract NAS 8-20290

1. A Comparison of Flexible and Rigid Ring Baffles for Slosh Suppression
2. Experimental and Theoretical Studies of Liquid Sloshing at Simulated Low-Gravity
3. Simulated Low-Gravity Sloshing in Cylindrical Tanks Including Effects of Damping and Small Liquid Depth
4. Simulated Low-Gravity Sloshing in Spherical, Ellipsoidal, and Cylindrical Tanks
5. A Theory for Low-Gravity Fuel Sloshing in an Arbitrary Axisymmetric Rigid Tank